JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 45, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2009

EFFECTS OF FOREST COMPOSITION AND SPATIAL PATTERNS ON STORM FLOWS OF A SMALL WATERSHED[1]

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ABSTRACT: The PRMS_Storm model was built as a storm event, distributed hydrological model for studying the hydrological effects of forest composition and spatial distribution on storm-flow volume and peakflow rates in the Xiangshuixi Watershed in the Three Gorges Reservoir Area, in the Yangtze River Basin in southwestern China. We developed three simulation scenarios based on forest composition and their spatial arrangements across the watershed, including all mixed conifer-evergreen broadleaf forests (Scenario 1), all mixed evergreen broadleaf forests (Scenario 2), and mixed conifer + evergreen broadleaf + shrub forests (Scenario 3). We examined 11 storm events observed during 2002-2005. Compared with the existing forest covers, modeling results suggested that the amount of overland flow was reduced by 21, 23, and 22%, and the interflow increased by 16, 88, and 30%, for Scenarios 1, 2, and 3, respectively. During the same time, peakflow rates were reduced by 20.8, 9.6, and 18.9%, respectively. The reduction of peakflow rates was most significant when rainfall intensity exceeded 0.8 mm/min and events with a short duration and effect was minor when rainfall intensity was below 0.5 mm/min. In general, we found that Scenarios 1 and 3 were preferred for reducing storm-flow volume and peakflow rates due to their higher interception rates, large soil water holding capacity, and higher soil infiltration capacity. The modeled results suggested soil properties are important in affecting the flow processes and thus forest composition and forest spatial distributions will affect storm-flow volume and peakflow rates at the watershed scale. To maximize flood reduction functions of a watershed, high priority should be given to those forest types (Scenarios 1 and 3) in reforestation practices in the study region. This study suggests both forest composition and spatial pattern are important reforestation designs for flood reduction in the Three Gorges Reservoir Area.

(KEY TERMS: forest composition; PRMS_Storm; Three Gorges Reservoir Area; forest hydrology.)

Qi, Shi, Yunqi Wang, Ge Sun, Yubao Xiao, Jinzhao Zhu, Hailong Yang, Xiaojing Hu, Bin Wu, Yujie Wang, and Steve G. McNulty, 2009. Effects of Forest Composition and Spatial Patterns on Storm Flows of a Small Watershed. *Journal of the American Water Resources Association* (JAWRA) 45(5):1142-1154. DOI: 10.1111/j.1752-1688.2009.00350.x

[1]Paper No. JAWRA-07-0149-P of the *Journal of the American Water Resources Association* (JAWRA). Received November 6, 2007; accepted April 28, 2009. **Discussions are open until six months from print publication**.

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INTRODUCTION

Forests affect the watershed balances at multiple spatial and temporal scales through altering the evapotranspiration processes (Sun *et al.*, 2006). However, the relationships between forests and floods have been controversial throughout the history of forest hydrology around the world (Andréassian, 2004; Eisenbies *et al.*, 2007). Earlier studies by Lull and Reinhart (1972) in the eastern United States (U.S.) suggested that the effect of forest on floods diminishes as storm sizes increases. Chang (2002) concluded that for a given region, peakflow rates are generally lower in watersheds with a greater percentage of forest area. Forest cover can be effective for flood control in a small watershed and for storms of low intensity and short duration. Studies in the southern U.S. showed that the conversion of deciduous to coniferous forests, forests to grasses, forests to mountain grazing, and forests to farmlands all resulted in an increase of peakflow rates, but with very different magnitudes (Sun *et al.*, 2004).

In the middle and upper reaches of the Yangtze River, especially in the Three Gorges Reservoir Area in southern China, floods are common and soil erosion problems are serious. It is a well accepted concept by policy makers and scientists that forests play an important flood mitigation role in this area. However, little scientific data are available to support this perception. Nation-wide forest-flood relation discussion in China was heated after the 1998 flood on the Yangtze River that killed more than two thousand people and caused enormous economic loss in southern China. The peakflow of this flood was 80.4×10^3 m^3/s and was compared lower than the 1954 flood (92.6×10^3 m^3/s), but the water level of the 1998 flood was 2-3 m higher than that of 1954 (Shi and Zhang, 1998). Forest exploration on the upstream uplands and associated sedimentation downstream was believed to be the reason behind this contrast. For example, Ma (1998) reported that the destruction of forest cover in the upper reaches of the Yangtze River resulted in an 8.27 m^3/s increase in flood peaks. Xu (2000) showed that forests significantly elevated the runoff in the lowflow season and reduced the flood discharge in the same region. However, this study noted that effects of forest on reducing large floods caused by large and long duration rainstorms covering the entire river basin were limited. Experiments in the Zangunao Watershed, in the Min River, an upper reach of the Yangtze River, showed that a 10% decrease in forest coverage caused a 26.3-mm increase in runoff (Sun, 2001). In general, case studies in southern China suggest that forests could reduce peakflows by 50% in watersheds with an area <10 km^2. The effects are smaller for large basins or large storms (Fei and Yang, 2002). Most studies in China focused on the effects of forest cover extent on stream flow and floods and studies on the hydrological effects of forest composition and spatial distributions on storm flows were rare.

Many factors affect the complex forest-flood relationships. Physically-based distributed models have been widely used to predict the hydrological effects of watershed management, and have been acknowledged as the most effective method in hydrologic research (Andersen *et al.*, 2001; Legesse *et al.*, 2003; Eisenbies *et al.*, 2007). Dramatic variations in flood severity and intensity call for analyses that focus on a watershed scale, much finer than global or continental ones (Bronstert *et al.*, 2002). Assessing forest effects on floods requires hydrological models that describe the hydrological process (Singh, 1995).

Therefore, the objectives of the study were as follows: (1) to use a distributed hydrological model to study the effects of forest composition and spatial pattern on storm-flow volume and peakflows of a forested watershed, (2) to explore the mechanisms of how reforestation practices may affect storm-flow volume and peakflows, and (3) to explore using model results to design reforestation practices to maximize the flood reduction functions.

METHODS

Watershed Characteristics

The Xiangshuixi Watershed (28°31′-28°46′N, 106°17′-106°31′E) selected for this simulation study is located on Simian Mountain in the Three Gorges Reservoir Area. The area of the watershed is about 8.0 km^2. The climate is humid, characteristic of the subtropical monsoon region. The mean annual air temperature is 13.7°C and annual precipitation is 1,550 mm. A digital elevation model (DEM) was derived by digitalizing a geographical map with a 1:10,000 scale (Figure 1a). The average elevation of the watershed is 1,180 m, ranging from 1,000 m to 1,400 m above the sea level. The average slope is about 40°. The average length and width of the stream flow path is 783 and 5.4 m respectively. The channel gradient is estimated as about 15%. The land use and soil data were derived from field surveys. The watershed is dominated by evergreen broadleaved forests with a high canopy coverage ranging from 0.7 to 0.95. The major soil type is loam of Alumi-Ferric. The thickness of most soils was over

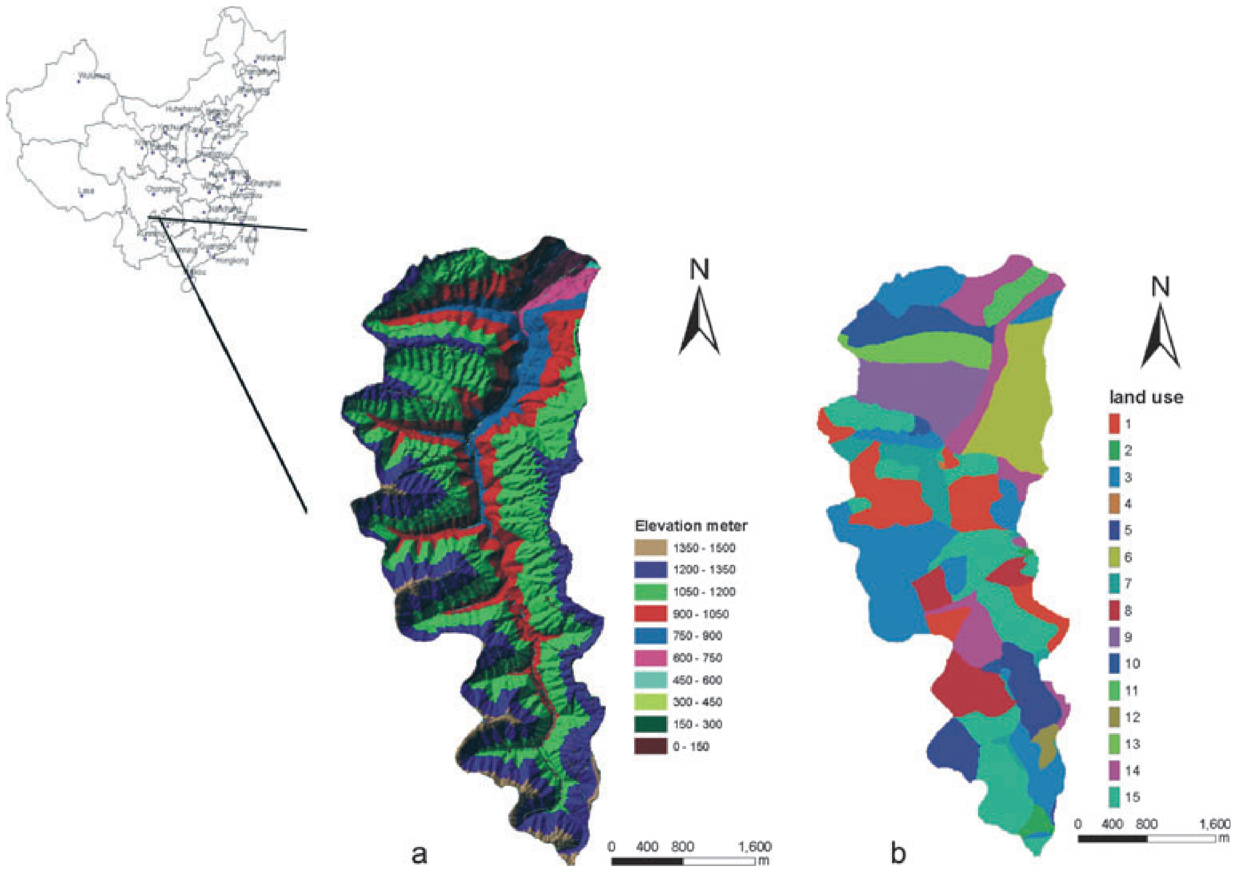

FIGURE 1. Topographic Elevation (a) and Forest Types (b) of Xiangshuixi Watershed. Forest type classifications: COF (2. *Pinus armandii*, 3. *Cunninghamia lanceolata*, 7. *Cryptomeria fortunei*); BRD (1. *Castanopsis fargesii*, 4. *Populus*, 5. *Castanea mollissima*, 6. *Pterocarya stenoptera*, 8. *Quercus*, 10. *Cinnamomum camphora*); MCB (13. mixed conifer-conifer forest, 14. mixed conifer-broadleaf forest); MIB (15. mixed broadleaf-broadleaf forest); BMB (9. *Phyllostachys pubescens*); SHB (11. shrub forest); GRA (12. wild grassland).

1 m, and the soils had high porosity and high infiltration capacity, ranging from 1.7 to 4.0 mm/min.

Forest Covers

The forest covers were classified as six types, pure coniferous forests (COF), pure broadleaf forests (BRD), mixed conifer-broadleaf forests (MCB), bamboo forests (BMB), mixed evergreen broadleaf forests (MIB), and shrub forests (SHB), accounting for 20.3, 33.6, 13.5, 0.1, 31.5, and 0.9% of the total watershed area, respectively. In addition, grassland (GRA) accounted for 0.18% of the watershed area (Figure 1b). The COF includes fir (*Cunninghamia lanceolata*), Japanese cedar (*Cryptomeria fortunei*), and Masson pine (*Pinus armandii*) forests. Most fir and Japanese cedar stands are man-made plantations with a simple stand structure, and are generally distributed on high elevation above 1,000 m. The Masson pine is a typical tree species found on south facing slopes with acid soils that are derived from sand and shale rocks with an elevation of about 1,000 m. MCB have a complex layer structure and tree species that include fir, Masson pine, and various broadleaved trees, which grow on the thick and well drained nutrient-rich soils. They are located mostly in the upper part of low-relief slopes and collocated with shade and humidity-tolerant broadleaved species. The BRD are dense vegetation communities distributed at an altitude about 1,500 m and grow on upland loam of Haplic Alisols. MIB grow on warm and humid sites on mod-slopes below an elevation of 1,300 m. They consist of rich species and can tolerate minor human disturbances. The BMB are mostly cultivated communities with a simple structure, with few shrubs, but with an abundant grass layer. The SHB consists of evergreen shrubs originated from natural forests with a rich plant biodiversity and dense growth.

Storm-Flow Measurements

Storm-flow rates at the watershed outlet were measured with a flat V notch weir and an automatic water stage recorder equipped with a WGZ-1 fluviograph (Chongqing Youpeng STL. Co. Ltd., China). Stage values were converted to discharge with a 15-min time interval using a standard stage-discharge relationship. Meteorological variables such as precipitation, wind speed, evaporation, air temperature and humidity, and soil temperature and moisture were measured at a 15-min time interval by a set of fully automated devices outside the forests. Precipitation data were recorded by a B-432-Z automatic hyetometer (Chongqing Youpeng STL. Co. Ltd.).

The Precipitation Runoff Modeling System Model

We constructed the PRMS_Storm model using the Modular Modeling System (MMS) (Leavesley *et al.*, 1983, 2002) that was originally developed by the U.S. Geological Survey. MMS consists of three parts. The first part is the pre-processor including Graphical User Interface (GUI) and Geographic Information System (GIS) Weasel (U.S. Geological Survey, available at http://pubs.usgs.gov/fs/) to acquire and process input data. The second part includes model building by using a module library, parameter-optimization and sensitivity analysis utilities that optimize selected model parameters and evaluate their individual and joint effects on model outputs. The third part is a post-processor that includes visualization, result statistics, and Decision Support System (DSS). There are a total of 38 modules within MMS that can be selected to build new models for different purposes. The rainfall-runoff processes modeled by MMS were presented in Figure 2. A total of 19 modules related to storm events were used in PRMS_Storm. We used this modeling system to examine the effects of vegetation combinations and its spatial distribution on storm-flow volume and peakflows.

Hydrological Response Units Delineation

The study watershed is divided into subunits based on its physical characteristics such as slope, aspect, elevation, vegetation type, soil type, land use, and precipitation distribution. A total of 28 hydrological response units (HRUs) were delimitated by using the Arc/Info software (ESRI China, Beijing, China). The hydrographic net generated from a DEM was overlaid with land cover and soil maps. Each HRU was assumed to be homogeneous with respect to its soil, vegetative cover, slope, aspect, elevation, and precipitation distributions. The mean HRU area is 0.29 km^2, ranging from 0.04 km^2 to 0.77 km^2. HRUs

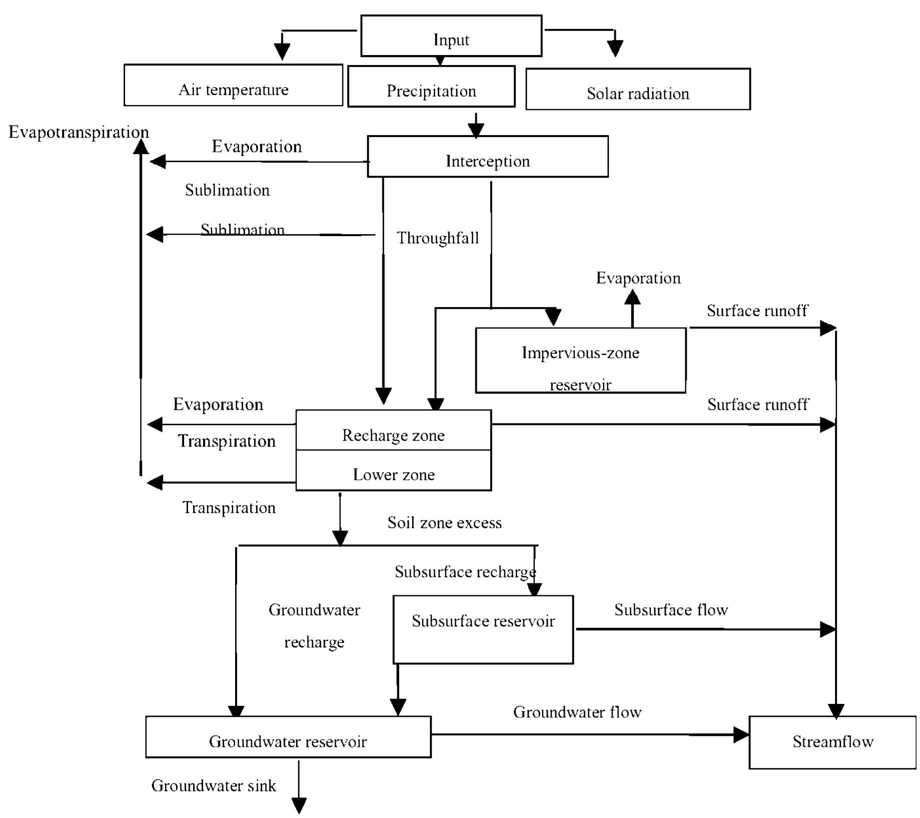

FIGURE 2. Components and Processes of PRMS_Storm Model.

are linked to adjacent channel segments for flow routing.

Peakflow and Hydrograph Modeling

For storm hydrograph simulations, the watershed is conceptualized as a series of interconnected flow planes and channel segments (Figure 2). An HRU can be considered the equivalent of a flow plane. Surface runoff is computed for each HRU and each time step, based on a soil moisture balance and the antecedent soil moisture and rainfall amount. Surface runoff as precipitation excess is routed to the stream via a kinematic wave approximation of overland flow. Subsurface flow is the relatively rapid movement of water from the unsaturated zone to the stream channels. The source of subsurface flow is soil water in excess of soil field capacity, and subsurface flow also is routed to the adjacent channel segment. Channel flow then is routed kinematically through each segment and then to the basin outlet.

Key Model Parameters

The PRMS_Storm model requires 145 parameters and input variables. Most parameters about watershed and channel characteristics such as the slope, channel length, and width can be determined from DEM and land use maps. The default values for some parameters such as monthly air temperature coefficient and monthly factor to adjust rain proportion that do not directly affect the process of single storm events, were used. However, some key parameters were measured in the field to initialize model runs. A plot with a size of 20 m by 30 m was established in each forest type for determining these key model parameters. Table 1 presents the nine key parameters that are sensitive to the model efficiency, including canopy interception rates and density, cover degree, water holding capacity of litter, soil hydraulic conductivity, and initial soil water content conditions. Key vegetation parameters of the six forest types (COF, BRD, MCB, BMB, MIB, and SHB) such as canopy density, shrub and grass layer coverage were surveyed in the field. Understory properties were quantified with field sampling.

Soil samples were collected in the upper, middle, and lower slopes with three replications each and saved for subsequent bulk density, soil porosity, and particle size distribution measurements in the laboratory. Soil water holding capacity and soil texture were determined in the laboratory. The soil infiltration capacity was determined on site using a double-ring infiltrometer with a 15-cm diameter inter ring and a

TABLE 1. Major Soil and Vegetation Parameters Used in PRMS_Storm.

	Canopy			Litter	Soil Horizon				
Forest Type	**Maximum Interception (mm)**	**Canopy Density**	**Shrub and Grass Cover Degree (%)**	**Maximum Water Holding Capacity (mm)**	**Hydraulic Conductivity (mm/min)**	**Soil Moist Initial (mm)**	**Soil Moist Max (mm)**	**Soil Recharge Initial (mm)**	**Soil Recharge Max (mm)**
COF (pure conifer forest)	0.6	0.80	0.4	3.2	7.0	52.4	97.8	8.4	9.8
BRD (pure broadleaf forest)	0.2	0.90	0.7	4.4	7.0	42.7	55.5	13.6	18.0
MCB (mixed conifer-broadleaf forest)	0.4	0.85	0.5	4.7	7.6	78.6	97.8	12.7	39.2
MIB (mixed broadleaf forest)	0.2	0.80	0.6	4.3	7.6	92.1	97.1	15.4	47.4
BMB (bamboo forest)	0.8	0.80	0.9	3.3	7.4	60.7	77.9	13.0	37.3
SHB (shrub forest)	1.0	0.90	0.3	8.1	8.5	142.4	145.8	22.6	69.6
GRA (wild grass ground)	0.0	0.00	0.9		5.9	9.4	34.9	6.9	8.0

30-cm diameter outer ring. A constant head test was used (Gregory *et al.*, 2005). Litter depth was measured on site. Litter water holding capacity was determined in house by the weight differences between socking in water for 24 h and drying at 70°C for 48 h.

Runoff including surface runoff and groundwater runoff on each experiment plot (20 m by 5 m) was recorded at a 10-min time scale, which will be used to divide runoff component for stream flow on watershed scale. Throughfall, overland flow, and interflow were also measured. Some model parameters such as soil water holding capacity were optimized by using the Rosenbrock optimization procedure (Rosenbrock, 1960).

Model Evaluation Criteria

The Nash-Sutcliffe efficiencies (E) and the correlation coefficient (R) were used to provide statistical evaluation of model performance (Nash and Sutcliffe, 1970).

$$E = \frac{\sum_1^N (Q_{oi} - Q_o)^2 - \sum_1^N (Q_{oi} - Q_{si})^2}{\sum_1^N (Q_{oi} - Q_o)^2}, \tag{1}$$

where Q_{oi} is the observed runoff for time i, Q_{si} is the simulated runoff for time i, Q_o is the average observed runoff, N is the time-interval number.

Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 (E = 1) corresponds to a perfect match of modeled discharge to the observed data. An efficiency of 0 (E = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency <0 ($-\infty < E < 0$) indicates the model is not very useful for prediction purpose. The PRMS_Storm model was evaluated by its prediction of runoff at a 15-min temporal scale as the observed discharge.

According to the national standard of "Hydrological Information Forecasting Codes SL250-2000" as developed by the Ministry of Water Resources of China, the allowable errors for storm-flow volume and peakflows are ±20% of the measured value. The prediction errors for time to peak should not exceed three hours. In this study, the model performance and flood forecast accuracy were determined by E and percentage of events meeting the national flood forecasting standard. We set flood forecast accuracy as two levels, First Level (percentage meeting the standard ≥85% and $E > 0.9$) and Second Level (85% > percentage meeting the standard ≥70% and $0.9 \geq E \geq 0.7$).

Modeling Scenarios

Based on the observed runoff process observed at the slope plot level (100 m^2 plots) covered with four different forest types, the hydrological functions of evergreen broadleaf forest were considered the most efficient in reducing surface runoff and runoff peaks (Wang *et al.*, 2005). According to the hydrological functions of 12 forest sampling plots evaluated using the Analytic Hierarchy Process (AHP) (Forman and Selly, 2002) and the comprehensive grading method, mixed fir + Masson pine + broadleaf forests were the best to reduce overland flow in the study watershed (Wang, 2006). From the observation data, three simulation scenarios were developed to study how the combinations of forest types affect storm-flow volume and peakflow rates (Table 2). Scenario 1 included conversion of existing forest composition to mixed conifer + broadleaf forests and Scenario 2 included evergreen broadleaf forests. The shrub forests in the watershed had better site adaptability than other forest types. Considering forest distribution patterns and elevation gradients and slopes, Scenario 3, mixed conifer + evergreen broadleaf + shrub forests (comprehensive arrangement pattern) were developed as one of the optional forest types (Table 2).

RESULTS

Characteristics of Rainstorm Events

We used 11 rainstorm events recorded during 2002-2005 in this study (Table 3). The duration of the rainstorm was usually longer than 12 h. The amount of total rainfall varied from 46 to 104 mm, but most

TABLE 2. Scenarios of Forest Type Arrangement Patterns for Xiangshuixi Watershed.

Baseline	Scenario 1	Scenario 2	Scenario 3	Slope (°)	Altitude (m)
COF (pure conifer forest)	All forests converted to mixed conifer-broadleaf forests	All forests converted to mixed broadleaf forests	Mixed conifer-broadleaf forest	30-40	1,000-1,100
BRD (pure broadleaf forest)			Mixed broadleaf forest	30-40	1,100-1,200
MCB (mixed conifer-broadleaf forest)			Mixed conifer-broadleaf forest	40-45	1,000-1,100
MIB (mixed broadleaf forest)			Mixed broadleaf forest	30-40	1,200-1,400
BMB (bamboo forest)			Mixed broadleaf forest	40-45	1,200-1,400
SHB (shrub forest)			Shrub forest	45-50	1,000-1,400
GRA (wild grass ground)			Mixed conifer-broadleaf forest	40-45	1,100-1,200

TABLE 3. Precipitation Characteristics of 11 Observed Storms in the Xiangshuixi Watershed.

Rainstorm Event	Date	Rainfall (mm)	Duration (h)	Rainfall Peak (mm/min)	Average Rainfall Intensity (mm/min)
1	04/13/2003-04/15/2003	46.2	18 h 45 min	0.493	0.041
2	07/03/2003-07/05/2003	93.0	27 h 30 min	1.413	0.035
3	07/18/2003-07/20/2003	84.4	24 h 15 min	1.320	0.056
4	04/06/2004-04/09/2004	85.2	30 h 45 min	1.707	0.046
5	04/23/2004-04/25/2004	81.3	12 h	0.847	0.093
6	05/29/2004-06/02/2004	85.0	27 h 15 min	0.373	0.051
7	09/04/2004-09/05/2004	104.4	16 h 45 min	7.200	0.104
8	09/30/2004-10/01/2004	50.4	18 h 45 min	0.360	0.045
9	04/25/2005	75.0	8 h	0.800	0.156
10	05/01/2005	59.4	5 h 15 min	1.520	0.189
11	05/05/2005	85.8	6 h 45 min	1.947	0.212

Note: Dates are in mm/dd/yyyy format.

events exceeded 80 mm. The averaged rainfall intensity ranged from 0.035 to 0.212 mm/min. Rainstorms peaked at greater than 0.37 mm/min and could reach a maximum of 7.2 mm/min.

Model Calibration and Validation

The model performance for the calibration and validation periods was evaluated by E and R (Table 4). Model calibrations suggested that the nine most sensitive parameters were canopy interception and density, cover degree, water holding capacity of litter, hydraulic conductivity, and four soil water contents values.

The six storm runoff events (Storm #1 to #6) were used for PRMS_model calibration. For each storm event, the Rosenbrock optimization procedure was applied until the average E of six storm_runoff events reaching its maximum, and the optimal values of these parameters were derived (Table 1).

Two hydrographs of all six calibration storms (Storm #1 to #6) are presented in Figure 3. For those two events, E and R were > 0.7 and 0.8, respectively. The prediction error for storm-flow volume was 2.2%, and peakflow rate prediction error was 15.4% (Table 4). Therefore, the predictions met the Second Level of national prediction standard, showing that the model performance was acceptable.

The other five storm events (Storm #7 to #11) were used for model validation (Figure 4). The averaged E was approximately 0.7 and R was 0.85 (Table 4). The prediction errors for storm-flow volume and peakflows for a majority of the simulations were considered good. In general, the performance accuracy and satis-

TABLE 4. Simulated and Observed Storm Flow and Peakflow of Xiangshuixi Watershed for Calibration and Validation Periods.

Storm Event	Date	Observed Storm Flow (mm)	Observed Peakflow (mm/min)	Simulated Storm Flow (mm)	Simulated Peakflow (mm/min)	E	R	Runoff Error (%)	Peak Error (%)	Peak Occurred Time Difference
Calibration										
1	04/13/2003-04/15/2003	14.1	0.014	13.8	0.013	0.83	0.92	2.5	10.1	2 h 45 min
2	07/03/2003-07/05/2003	32.3	0.053	32.2	0.046	0.63	0.83	0.3	13.2	1 h 30 min
3	07/18/2003-07/20/2003	30.1	0.056	24.5	0.048	0.74	0.90	18.4	14.3	0 min
4	04/06/2004-04/09/2004	51.3	0.081	43.2	0.060	0.72	0.94	15.8	**25.9**	15 min
5	04/23/2004-04/25/2004	28.7	0.052	31.3	0.046	0.52	0.75	−9.1	11.5	15 min
6	05/29/2004-06/02/2004	39.6	0.025	46.9	0.025	0.75	0.94	−18.2	0.0	15 min
Average		32.7	0.047	32.0	0.040	0.70	0.88	2.2	15.4	50 min
Validation										
7	09/04/2004-09/05/2004	32.7	0.152	36.7	0.151	0.92	0.88	12.4	−0.7	30 min
8	09/30/2004-10/01/2004	11.6	0.024	12.1	0.020	0.71	0.80	4.0	−19.6	15 min
9	04/25/2005	16.8	0.076	20.0	0.072	0.62	0.85	19.2	−5.3	15 min
10	05/01/2005	9.1	0.040	10.8	0.047	0.62	0.86	18.4	17.5	15 min
11	05/05/2005	9.85	0.038	13.17	0.047	0.52	0.85	**33.71**	**23.68**	30 min
Average		11.84	0.07	18.55	0.07	0.68	0.85	17.54	3.12	21 min
Percentage meeting the standard (%)								4/5 = 80	4/5 = 80	100

Notes: Dates are in mm/dd/yyyy format.
Bold numbers signify the error is not in the allowable errors for this storm event.

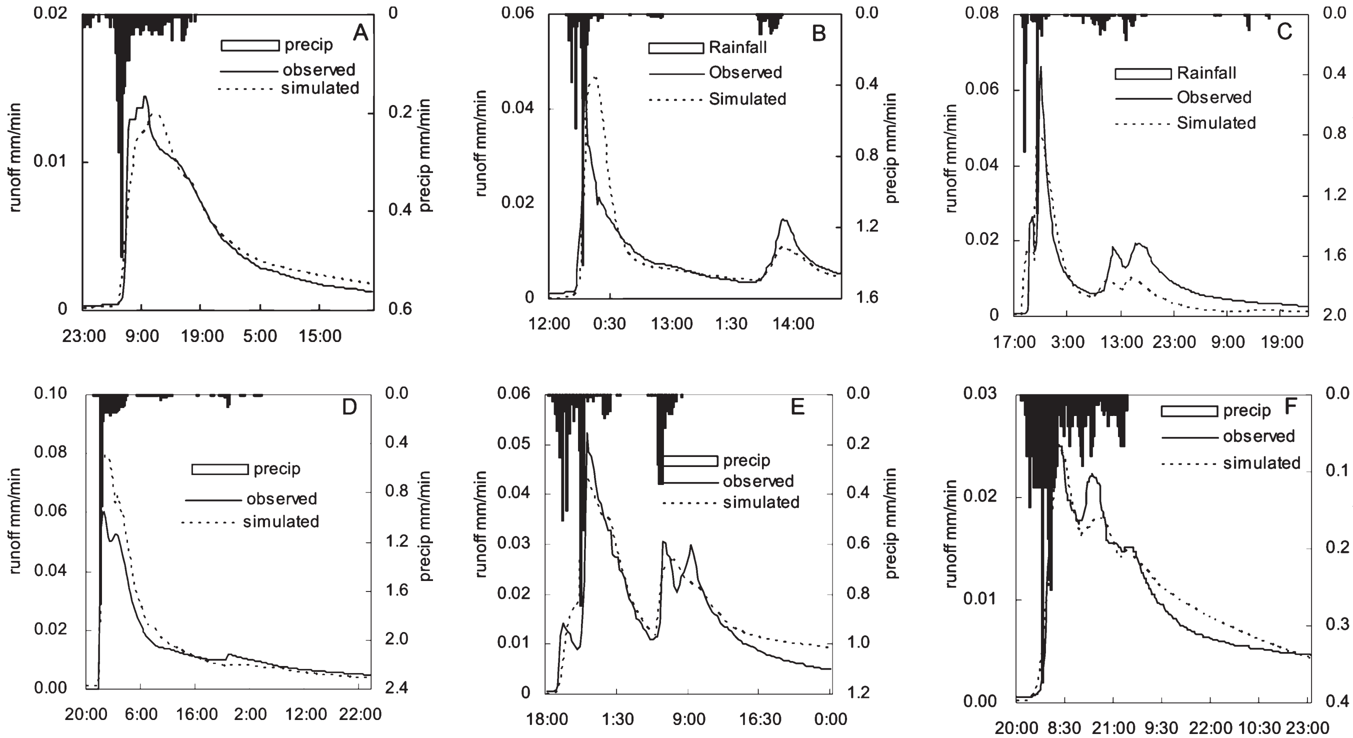

FIGURE 3. Simulated Hydrographs of Xiangshuixi Watershed (Calibration).
A: Storm #1; B: Storm #2; C: Storm #3; D: Storm #4; E: Storm #5; F: Storm #6.

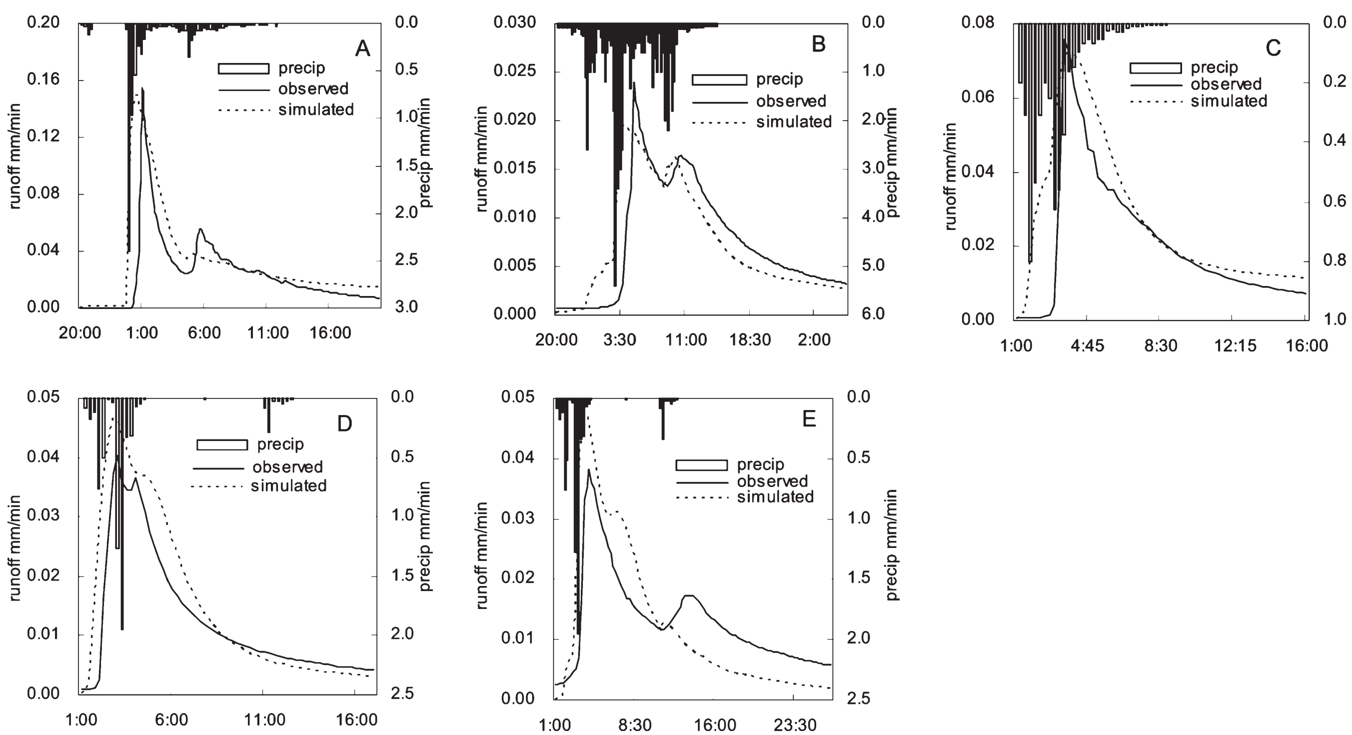

FIGURE 4. Simulated Hydrographs of Xiangshuixi Watershed (Validation).
A: Storm #7; B: Storm #8; C: Storm #9; D: Storm #10; E: Storm #11.

TABLE 5. Simulated Peakflows by PRMS_Storm Under Three Scenarios in the Xiangshuixi Watershed.

Storm Event	Date	Baseline	Peakflow (mm/min)			Reduction Percent		
			Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
1	04/13/2003-04/15/2003	0.013	0.012	0.017	0.014	8.5	−25.8	−3.1
2	07/03/2003-07/05/2003	0.046	0.042	0.045	0.042	9.0	2.6	9.2
3	07/18/2003-07/20/2003	0.048	0.033	0.036	0.033	30.5	24.7	31.3
4	04/06/2004-04/09/2004	0.060	0.044	0.050	0.045	26.3	16.9	24.9
5	04/23/2004-04/25/2004	0.046	0.032	0.038	0.033	30.1	18.0	27.6
6	05/29/2004-06/02/2004	0.025	0.025	0.030	0.026	−0.1	−20.6	−5.1

Note: Dates are in mm/dd/yyyy format.

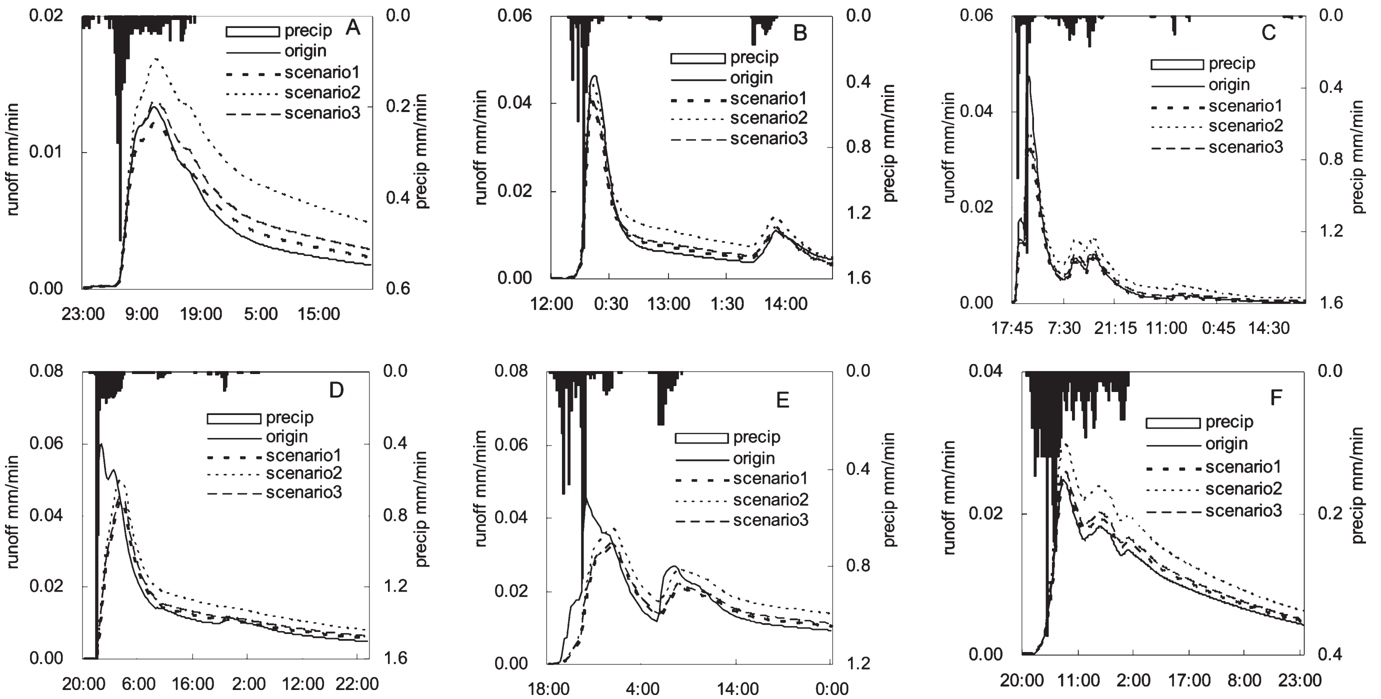

FIGURE 5. Storm Flow Hydrographs Under Three Scenarios of Xiangshuixi Watershed.
A: Storm #1; B: Storm #2; C: Storm #3; D: Storm #4; E: Storm #5; F: Storm #6.

factory rates fell within the Second Level of national prediction standard, suggesting that the PRMS_ Storm model met the standards for official flood forecasting in the research area.

Hydrological Effects of Vegetation Compositions

Effects of Rainfall Intensity. The six rainstorm events (Storm #1 to #6) selected for model calibration were used to study the combined effects of the three hypothetical vegetation scenarios (Table 5). Compared to existing forest covers in the watershed, forest composition changes did not affect storm-flow peaks for Storm events #1 and #6 that had a maximum rainfall intensity <0.5 mm/min. In this case, the peakflows actually increased by 25.8%. However, forest composition change affected storm-flow peaks for Storm #2 to #5, with rainfall intensity greater than 0.8 mm/min. Therefore, peakflow reductions by the three scenarios were small for storm events with low rainfall intensity, but for other storm events the impacts were large. Compared with the existing forest cover, the peakflow rate was reduced by 9-31% for Scenario 1, 3-25% for Scenario 2, and 9-31% for Scenario 3 (Table 5).

Effects of Forest Compositions. For all rainstorms, Scenarios 1 and 3 had higher peakflow reductions than Scenario 2 in general (Table 5). Taking Storm #5 as an example (Figure 5), Storm #5 had a rainfall peak of 0.85 mm/min, a 12-h rainfall duration, and an average rainfall intensity of 0.093 mm/min. In this case, compared with the existing

TABLE 6. Evaluation on Runoff Under Three Scenarios in the Xiangshuixi Watershed

	Runoff (mm)			Total Storm Flow	% of Total Storm Flow			Peakflow (mm/min)	% Change Peakflow	Storm Flow Volume
	Surface Runoff	Interflow	Base Flow		Surface Runoff	Interflow	Base Flow			
Baseline	15.9	12.8	3.3	32.0	50	40	10	0.040		
Scenario 1	12.6	14.9	3.1	30.6	41	49	10	0.031	−20.8	−4.6
Scenario 2	12.1	24.1	3.7	39.9	30	60	9	0.036	−9.6	24.8
Scenario 3	12.4	16.7	3.4	32.5	38	51	11	0.032	−18.9	1.6

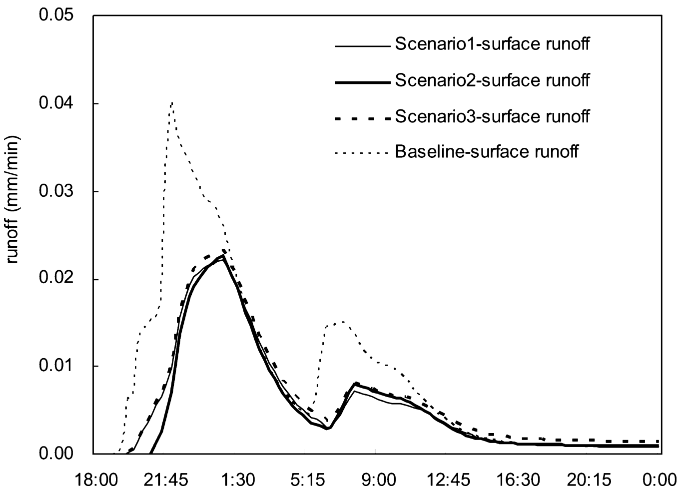

FIGURE 6. Simulated Surface Runoff Under Three Scenarios for Storm #5, Xiangshuixi Watershed.

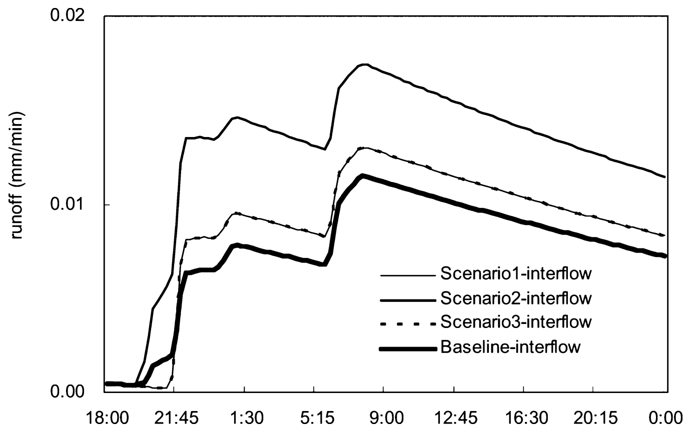

FIGURE 7. Simulated Interflow Under Three Scenarios for Storm 5, Xiangshuixi Watershed.

forest cover, storm-flow peaks were reduced by about 18-30% under these three scenarios. For the first peak, compared with the current forest covers, there was a 30% reduction in peakflow rates for Scenario 1, an 18% reduction for Scenario 2, and a 19% reduction for Scenario 3. The time to the first peak was delayed by about 3 h and 15 min in all three scenarios. For the second peak, there was a 22, 3, and 19% reduction for Scenarios 1, 2, and 3, respectively. The time to the second peak was delayed about 30 min for all scenarios. Therefore, all three Scenarios showed somewhat positive hydrological effects in reducing peakflow and delaying time-to-peak. The modeling results showed that Scenario 1 was the largest in reduction of peakflow rate, followed by Scenario 3 and Scenario 2 (Table 5).

Forest types and their spatial distributions had significant hydrological effects on runoff compositions. Compared with the existing forest cover, the average surface runoff ratio of six storm events (surface runoff over the total storm flow) decreased from 50 to 41, 30 and 38% and the interflow ratio increased by 9, 20, and 11% (Table 6) for Scenarios 1, 2, 3, respectively. Scenario 1 could effectively convert the storm surface runoff into interflow, representing a positive hydrological effect. The volume of storm surface runoff was decreased by 21, 23, and 22% respectively on average with little difference among the three scenarios. Interflow was increased by 16, 88, and 30% for Scenarios 1, 2, and 3, respectively. Little changes were found for base-flow volumes among all three scenarios (Table 6). Taking Storm #5 of Scenario 1 as an example (Figures 6 and 7), the overland flow volume was reduced from 51 to 37%, the interflow increased from 44 to 58%, and the base flow remained unchanged and the overland runoff peaks were considerably decreased by 45% compared with the existing forest cover. For Scenario 2, the interflow increased more than the other two scenarios (Figure 7). There were no big differences in surface runoff and base flow among three scenarios.

Total storm-flow volume increased by 25% in Scenario 2, but was almost unchanged in Scenarios 1 and 3 (Table 6). Compared with the existing forest cover, peakflow rates were reduced by 20.8, 9.6, and 18.9% in Scenarios 1, 2, and 3, respectively (Table 6). In terms of reduction in storm-flow volume and peakflow rates, the forest composition and spatial distribution of Scenario 1 was the best, followed by Sceanario 3, and Scenario 2. These simulations suggest that both mixed conifer + broadleaf forest and mixed broadleaf forest have high potential to reduce storm-flow volume and peakflows. The spatial arrangements of mixed conifer-broadleaf forest, mixed broadleaf forest, and shrub forest in a watershed have potential hydrological effects on reducing peakflows.

DISCUSSION

Model Efficiency

The Nash-Sutcliffe coefficient of the calibrated PRMS_Storm model for the study watershed was approximately 0.7, suggesting that there were other factors not explained by the model. Pakin *et al.* (1996) attributed model errors in simulations of small watershed runoff to the modeler, the modeling system, the parameterization of the modeling system, or the data used in a simulation. Our previous studies suggest that the PRMS_Storm is effective in interpreting the watershed response mechanisms on floods (Qi *et al.*, 2006). For this simulation study, all data inputs came from the field observations. Measurement errors and how representative they are of the samples at the watershed scale are unclear and uncertainty analysis is needed. So, when applying this model to other small watersheds in the Three Gorges Reservoir Area, site specific parameters are needed to achieve high model efficiency. Further, after observing more storm events in more small watersheds, the experience gained from setting up the maximum and minimum predicted bounds and the observed discharge for a typical sequence of storms will be of help in determining appropriate bounds for future validation tests in the whole Three Gorges Reservoir Area.

Model Applications

The impacts of land use, forests in particular, on floods has generally been evaluated from research that aims at understanding the individual processes at a small spatial scale, such as a plot scale, together with research at the experimental catchment scale (Calder and Aylward, 2006). The PRMS_Storm model built for this study has been designed especially for the small watershed in the Three Gorges Reservoir Area to study the forest composition effects on floods. We combined the research at the small watershed with plot-scale observatons of four typical forest types to derive optimum model parameters. However, MMS can be used to build the distributed hydrological model PRMS for large scale studies. Because the land use change will increase the complexity of the interacting processes on the net effect, or "integrated effect," it becomes increasingly difficult to predict at large spatial scales (Calder and Aylward, 2006). Therefore, to apply our model to a large basin, the PRMS_Storm needs to be tested again. At large scales, increases in peakflows are not easily discerned or modeled (Calder and Aylward, 2006). The distributed model presented in this study has its uses in studying the effects of vegetation combined with its site on floods to complement limitations of paired watershed experiments (Brown *et al.*, 2005).

Model Parameters

Accurate model parameter is a key to reducing model errors. The infiltration properties of soil are important in controlling runoff generation in a small watershed. Soils under natural forests tend to be relatively porous with high infiltration rates and consequently low rates of surface runoff. Therefore, stream flow would occur primarily via subsurface storm flow. This suggests that watersheds dominated by broadleaved forest covers would have a larger subsurface flow component (Table 6). Theoretically, forests reduce floods by removing a proportion of the storm rainfall and by allowing the buildup of soil moisture deficits (Calder and Aylward, 2006). Floods caused by high rainfall intensity are more strongly influenced by land-surface conditions than floods caused by frontal precipitation (Bronstert *et al.*, 2002). Our study found that different storm intensity and canopy density and water interception of canopy, and shrub and grass cover are important parameters in affecting floods. Most importantly, the effects of soil moisture would be expected to be most significant for storm events, where the soil moisture might be a significant proportion of the storm rainfall (Lull and Reinhart, 1972). However, this is not necessarily true for plantation forests, particularly where no natural understory of vegetation is maintained (Calder and Aylward, 2006). In addition, evapotraspiration is a very important parameter in affecting water yield, and is the main process responsible for changes in water yield as a result of alterations in vegetation (Zhang *et al.*, 2001). The three scenarios of forest composition may affect all these processes (antecedent soil moistures, canopy interception, evapotranspiration, and overland flow).

CONCLUSIONS

The storm event hydrological model, PRMS_Storm, was validated and applied to one experimental watershed in the Three Gorges Reservoir Area. The Nash-Sutcliffe coefficient and correlation coefficient were 0.7 and 0.85, respectively. Model performances met the national flood prediction standards of China and it can be concluded that this model may be used for simulating storm events in small forest watersheds.

Compared with the existing forest covers, mixed conifer-broadleaf forest, mixed broadleaf forest and a comprehensive arrangement pattern reduced peakflows by 20.8, 9.6, and 18.9%, respectively, while they increased the interflow by 16, 88, and 30% respectively. The proposed spatial rearrangements of forests reduced peakflows by 10-21%. Effects of forests on peakflows of the small watershed vary with rainstorm types and duration. The mixed conifer-broadleaf forests and a comprehensive arrangement of forest cover (mixed conifer, evergreen broadleaf and shrub forests) were most suited to achieve hydrological benefits and thus may be adopted in reforestation practices in the study region. Future studies will test the model in a larger watershed to examine how watershed size affects forest-flood relationships.

ACKNOWLEDGMENTS

We thank the sponsorships of CSC (China Scholarship Council), NSFC (National Natural Science Foundation of China) (30571486 and 30671661), Southern Global Change Program, United States Department of Agriculture Forest Service, and the Forestry Supporting Project, State Forestry Administration, PR China (2006BAD03A1802).

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